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A LOW HEAT INLEAK CRYOGENIC STATION FOR TESTING HTS CURRENT LEADS FOR THE LARGE HADRON COLLIDER

A. Ballarino, A. Bézaguet, P. Gomes, L. Metral, L. Serio and A. Suraci

Abstract

The LHC will be equipped with about 8000 superconducting magnets of all types. The total current to be transported into the cryogenic enclosure amounts to some 3360 kA. In order to reduce the heat load into the liquid helium, CERN intends to use High Temperature Superconducting (HTS) material for leads having current ratings up to 13 kA. The resistive part of the leads is cooled by forced flow of gaseous helium between 20 K and 300 K. The HTS part of the lead is immersed in a 4.5 K liquid helium bath, operates in self cooling conditions and is hydraulically separated from the resistive part.
A cryogenic test station has been designed and built in order to assess the thermal and electrical performances of 13 kA prototype current leads.
We report on the design, commissioning and operation of the cryogenic test station and illustrate its performance by typical test results of HTS current leads.

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Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

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L. Serio and A. Suraci

LHC Division, CERN
1211 Geneva 23, Switzerland

ABSTRACT

The LHC will be equipped with about 8000 superconducting magnets of all types. The total current to be transported into the cryogenic enclosure amounts to some 3360 kA. In order to reduce the heat load into the liquid helium, CERN intends to use High Temperature Superconducting (HTS) material for leads having current ratings up to 13 kA. The resistive part of the leads is cooled by forced flow of gaseous helium between 20 K and 300 K. The HTS part of the lead is immersed in a 4.5 K liquid helium bath, operates in self cooling conditions and is hydraulically separated from the resistive part.

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INTRODUCTION

The reference design for the Large Hadron Collider[1] (LHC) at CERN is based on the generalised use of High Temperature Superconductor (HTS) current leads[2,3] so as to reduce the total liquefaction rate distributed over the eight cryogenic plants of the 27 km circumference future LHC machine.[4]

Cooling of conventional self-cooled leads would require a liquefaction rate of about 300 g/s, while the use of HTS leads would reduce the heat load into the liquid helium bath at nominal current by a factor of up to 19,[5] making use of the 20 K/0.13 MPa return gas to the refrigerators from the beam screen and magnet support cooling circuits.

The 8000 superconducting magnets of the LHC machine are cooled in a pressurized bath of superfluid helium at 1.9 K. Two electrical feed boxes at the end of each of the 8 sectors of the machine provide the warm-to-cold transition via the HTS leads down to 4.5 K, and via a lambda plate to feed the magnets at 1.9 K. The leads are integrated in the electrical feed boxes and connected to the magnets via Low Temperature Superconducting bus bars. A cryogenic distribution line, running along the magnets, provides the 4.5 K LHe

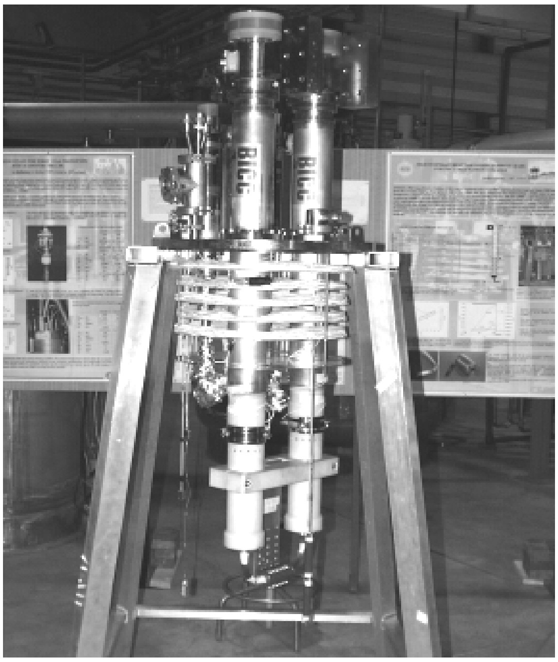

Figure 1. Prototype current leads prior to their installation in the test cryostat.

feeding of the leads bath and the 20 K GHe to ensure cooling of the resistive part. Warm gas from the leads and the LHe bath is recovered in a gas collector connected to the LP line of the refrigerator.

Prototype 13 kA HTS current leads have been specified by CERN and produced by several manufacturers in Europe, Japan and the US.

The specification defines the required thermo-electric performance and the geometric limitation imposed by the underground constraints of the accelerator. The proposed leads are composed of a resistive heat exchanger in which a flow of 20 K GHe is circulated and a HTS part that dips into the 4.5 K saturated helium bath. The temperature of the warm end of the HTS is controlled at or below 50 K by the flow of 20 K helium in the resistive heat exchanger. The vapor generated in the liquid helium bath is guided in a “skirt” surrounding the HTS element that is therefore operated in a self-cooling condition. The leads are optimised for operating at 13 kA with the warm end of the HTS below 50 K and the top part of the resistive heat exchanger at 290 K. Without current, the temperature of the gas outlet of the leads is maintained at 290 K by a thermostatically controlled heater at the warm terminal of the heat exchanger.

SYSTEM LAYOUT AND PRINCIPLES OF OPERATION

A low leat inleak cryogenic station for testing HTS current leads was designed in order to assess the thermal and electrical performance of the prototype leads ordered from industry. The cryostat provides the required working conditions: 4.5 K helium bath to cool the bottom part of the HTS leads, up to 2 x 1.2 g/s of 20 K helium gas to cool the resistive part of the leads, warm helium gas to quench the HTS, recovery of helium gas and the necessary instrumentation and valve actuators for control and diagnostic measurements. Furthermore, the design allows flexibility in the operation so as to optimize the control law for the optimum performance of the HTS current leads. The control and data acquisition system allows to monitor and automatically control transients such as cooldown, warm-up and current ramping/de-ramping, as well as steady-state operation.

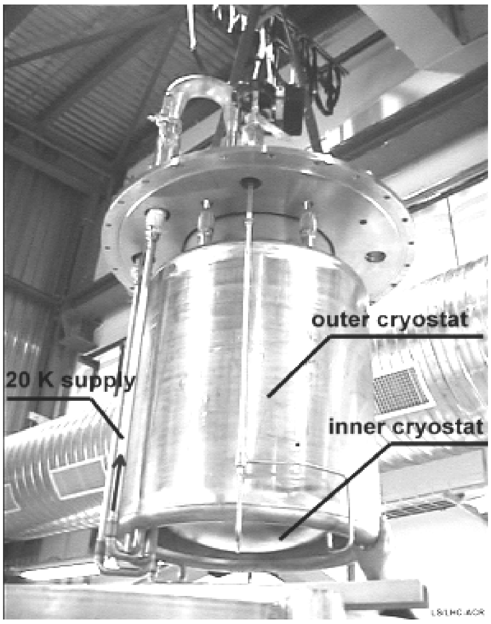

Figure 2. Inner and outer cryostat view.

System layout

As shown in figure 2, the test cryostat is composed of an annular (outer) cryostat providing radiation shielding at 4.5 K, neck thermal interception of the inner cryostat, and an inner cryostat in which the current leads are housed and cooled to maintain their nominal operating conditions. The two cryostats share a common insulation vacuum and are wrapped in multilayer thermal insulation.

The connection of the 20 K lines to the current leads in the inner cryostat is made via vacuum-insulated lines entering at and exiting from the top flange of the cryostats. This was necessary to allow easy demounting of the top flange of the inner cryostat to exchange current leads. Six radiation baffles in the inner cryostat provide thermal intercept of radiation from the top flange at ambient temperature. Gas from the inner and outer cryostats is warmed up via electrical heaters and recovered in a main manifold connected to the low pressure side of the refrigerator. The system makes use of the cryogenic infrastracture available, in particular a 6 kW @ 4.5 K cryogenic plant. Liquid helium is distributed via a vacuum-insulated and radiation-shielded transfer line, providing cooling and gas recovery for several test station. The outer cryostat is filled with liquid helium and acts as a supply of liquid for the inner cryostat via a cryogenic valve, and for cold gaseous helium for cooling the resistive part of the leads. An electrical heater can be used to increase the boil-off from the outer cryostat during powering of the leads when a higher mass flow is required. The inlet temperature of the gas supplied to the resistive part of the current leads is adjusted by mixing with 300 K gas.

Principles of operation

The test station has been designed for a maximum liquefaction requirement of about 4 g/s as shown in detail in Table 1.

The total nominal inventory of liquid helium in the two cryostats is about 150 l.

Two mass flow controllers adjust the necessary flow-rate to obtain the required gas temperature of 20 K. Additional electrical valves are used to add room temperature gas thereby increasing the temperature (up to 200 K) of the cooling flow in order to quench the

Table 1. Detailed design liquefaction requirements

Type of heat load	Equivalent load in g/s
1 pair of 13 kA leads in bath – 3 W	0.15
20 K cooling of leads	2.0
Anular cryostat – 5 W	0.25
Inner cryostat – 0.5 W	0.025
Transfer line and bayonet – 13 W	0.65
TOTAL	**3.075**
Design margin – 1.25	3.8

HTS. The gas is then recovered at the top part of each lead via an electro-pneumatic control valve, which regulates the mass flow in order to maintain the HTS warm temperature at or below 50 K. These valves can also control mass flow-rate depending on the current in the leads.

The pressure in the inner and outer cryostat is controlled via electro-pneumatic valves. The other electro-pneumatic control valve feeding LHe from the outer cryostat controls the level of liquid helium to cover the cold end of the HTS and the LTS short-circuit between the leads in the inner cryostat.

INSTRUMENTATION AND PROCESS CONTROL

Instrumentation

All the circuits’ temperatures are monitored with Platinum 100 sensors (300 to 25 K) and Carbon or CERNOX™ sensors (25 to 4.2 K). The current leads are equipped with a high-voltage insulated Platinum 100 sensor for control of the HTS warm-end temperature and several uninsulated Platinum 100 sensors distributed over the resistive part of the lead to measure its temperature profile. Two CERNOX™ sensors monitor the HTS middle and cold end temperatures.

Liquid levels are measured with superconducting wire gauges that can be pulsed to decrease their heat input to the liquid helium bath. Two gauges of different dimensions (500 mm and 100 mm length) are used in the inner cryostat for control and diagnostic respectively, in order to achieve higher accuracy. The inner cryostat has been calibrated to assess heat loads by rate of level decrease with time.

Helium flow is measured at ambient temperature using thermal mass (0.5 g/s of full scale reading with 1 % accuracy) and V-cone™ flowmeters (1.2 g/s of full scale reading with 1 % accuracy). In view of its accuracy over the full range, the first type is used to measure the boil-off from the leads bath; the second type is employed at the warm outlet of the current leads to measure the flow of 20 K helium gas, thanks to its precision and low pressure drop. The flowmeters have all been calibrated with GHe in operating conditions and re-calibrated in-situ at the lower part of their ranges.

Differential pressure sensors check the pressure drop in the resistive part of the lead.

Process control

The process control is performed using an industrial Programmable Logic Controller (PLC) in which the number of I/O channels is of the order of 30 and there are about 7 closed control loops. The automatic operation modes include cooldown, normal operation, quench and warm-up. This equipment is interfaced with an industrial supervision system based on PCVUE32™.

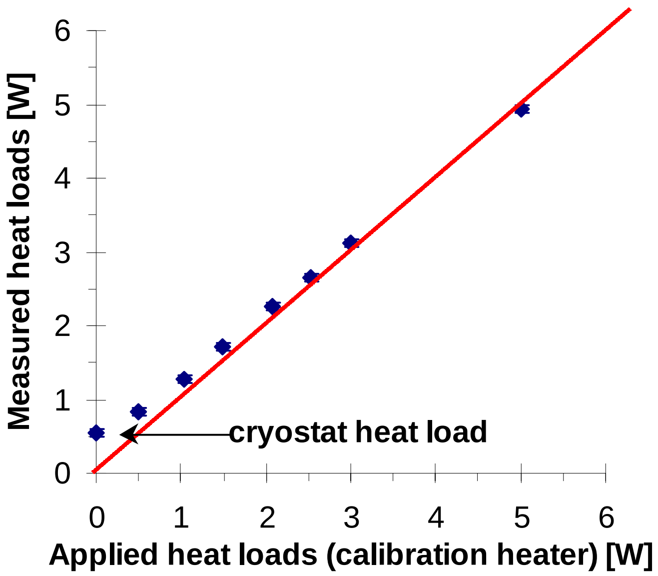

Figure 3. Test cryostat measured heat loads at various heater power (no leads).

The powering system of the leads is interlocked to the liquid level signal, the temperature of the warm part of the HTS and the cryogenic operator authorization.

The process control system is designed to run in fully automated mode 24h/24h. A shift operator is automatically called if a parameter of importance deviates from its expected range. The system can also be remotely accessed via Internet. Most of the experimental tests not involving powering of the leads are therefore performed overnight.

STAND-BY AND TRANSIENT OPERATION

Commissioning of the test cryostat

Prior to testing any of the prototype current leads, the cryostat underwent an extensive campaign of measurements to assess its thermal performance without leads. Furthermore, the cryostat itself, the instrumentation, the control and supervision system were fully commissioned and the instrumentation, where appropriate, re-calibrated in situ.

Cryostat characterisation

The HTS test cryostat needs about 24 h (with a flow of 0.2 g/s in the inner cryostat and 0.5 g/s in the outer cryostat) to reach stable operating conditions; this is mainly due to the masses involved and to the very good thermal insulation.

Once the cryostat is thermalized, the background heat loads (thermal conduction, radiation and superconducting liquid level gauge) in the inner cryostat can vary depending on the applied heat loads (current leads), which change the thermal characteristics of the cryostat (Figure 3).

During transient heat loads (changing the flow of evaporating helium from the bath), the neck and the radiative screen in the neck change their temperatures, thus varying the density of the helium in and around the radiative screen and modifying the steady-state flow measurements.

These two phenomena are taken into consideration to calculate the heat loads of the prototype current leads. A complete mapping of the thermal characteristics of the test cryostat at different applied heat loads prior to the insertion of the current leads allows one to determine the heat conducted to the 4.5 K liquid helium bath through the current leads with +/- 50 mW accuracy.

CRYOGENIC TESTS RESULTS

Each pair of leads requires at least one week to perform the specified performance tests. One week is also necessary to warm-up the cryostat, remove the previous leads, mount the new leads in the cryostat, check the instrumentation, condition the circuits and cool-down. A test program is established to study the behaviour of each lead in transient and stand-by operation.

Stand-by operation. The stand-by operation defines the thermal performance (Figure 4) of the leads with no current (heat loads in the liquid helium bath, flow-rate and pressure drop in the resistive part) at various HTS temperatures (30, 40 and 50 K).

Transient and steady operation. In transient operation we study the current ramping/de-ramping behaviour of the leads with 13 kA current (Figure 5), the behaviour of the lead during a loss of the 20 K helium flow cooling the resistive part with the current made to decay exponentially with a 120 seconds time constant, and the resistive transition of the superconducting part of the lead. In steady operation the thermal performance of the leads with 13 kA was observed.

The heat load in the liquid helium bath increases due to contact resistance when the leads are powered to 13 kA.

The self-cooling due to the skirt surrounding the HTS decreases the heat loads by pure conduction in the bath, thus reducing the absolute increase in heat loads when the leads are powered. This behaviour depends on the efficiency of the heat exchange in the HTS part.

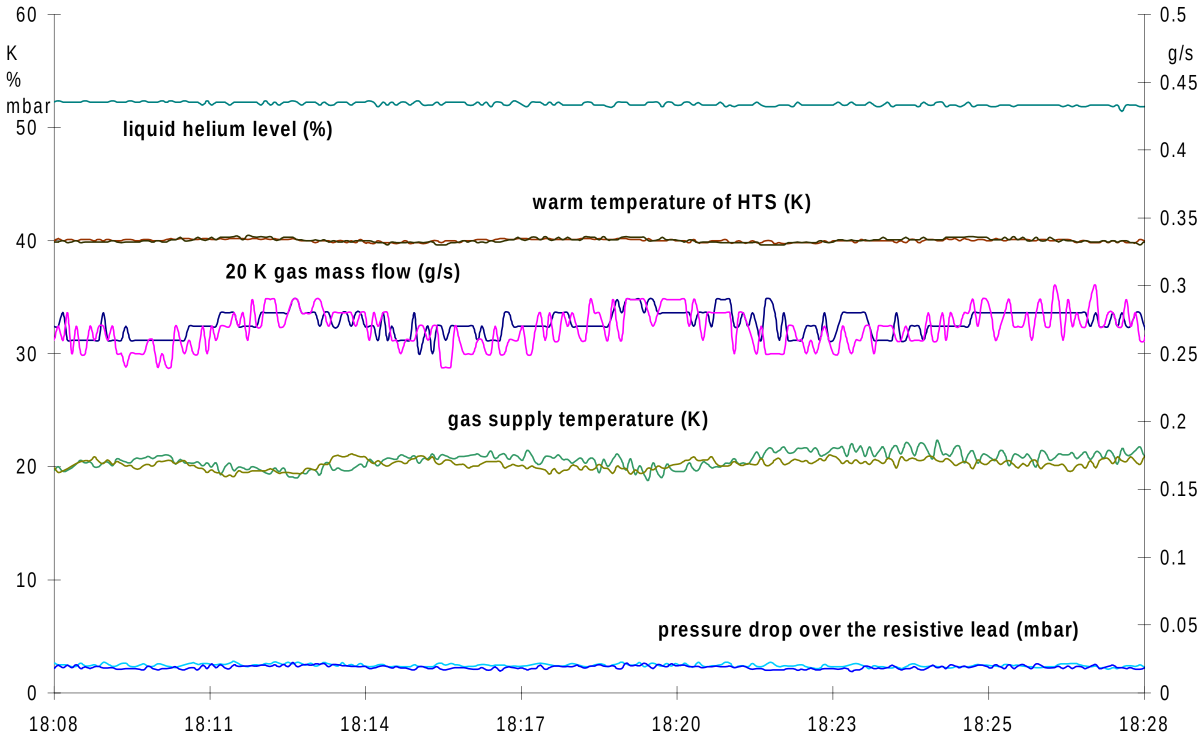

Figure 4. Typical steady-state thermal measurements on current leads (zero current).

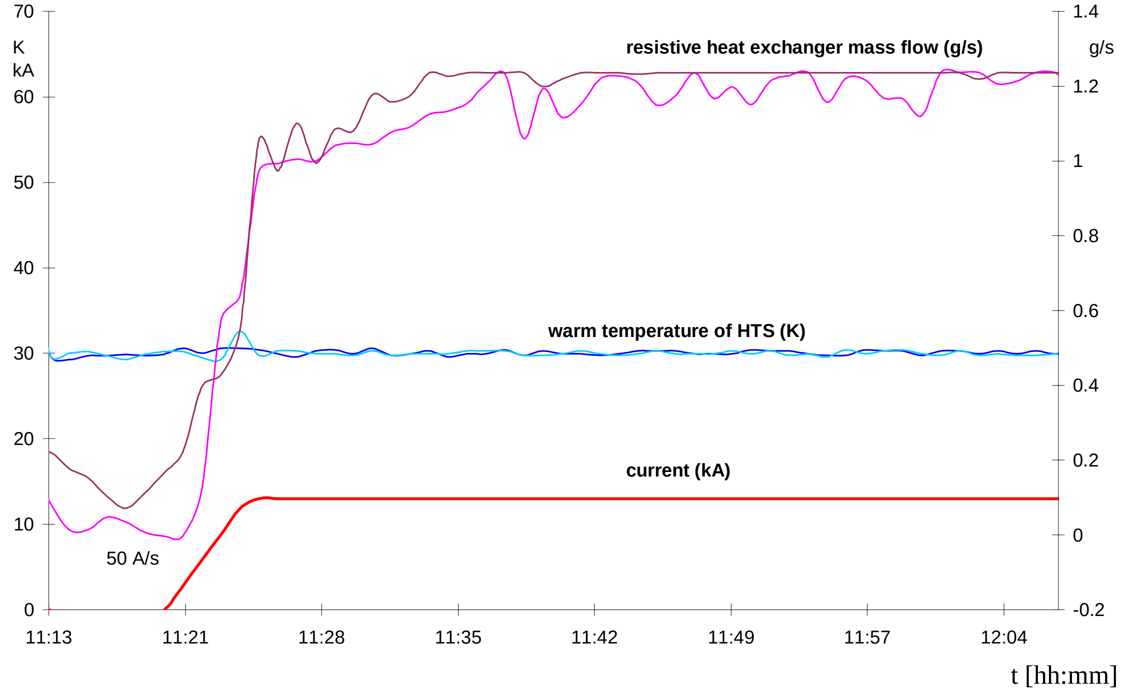

Figure 5. Typical response of cryogenic parameters during current ramping of leads.

Table 2 shows the typical cryogenic results obtained from a pair of HTS leads under test, including precision and stability. During stand-by, transient and steady operation the liquid helium level is maintained at its nominal value within +/- 0.25 cm, the precision of the liquid level gauge being +/- 0.1 cm.

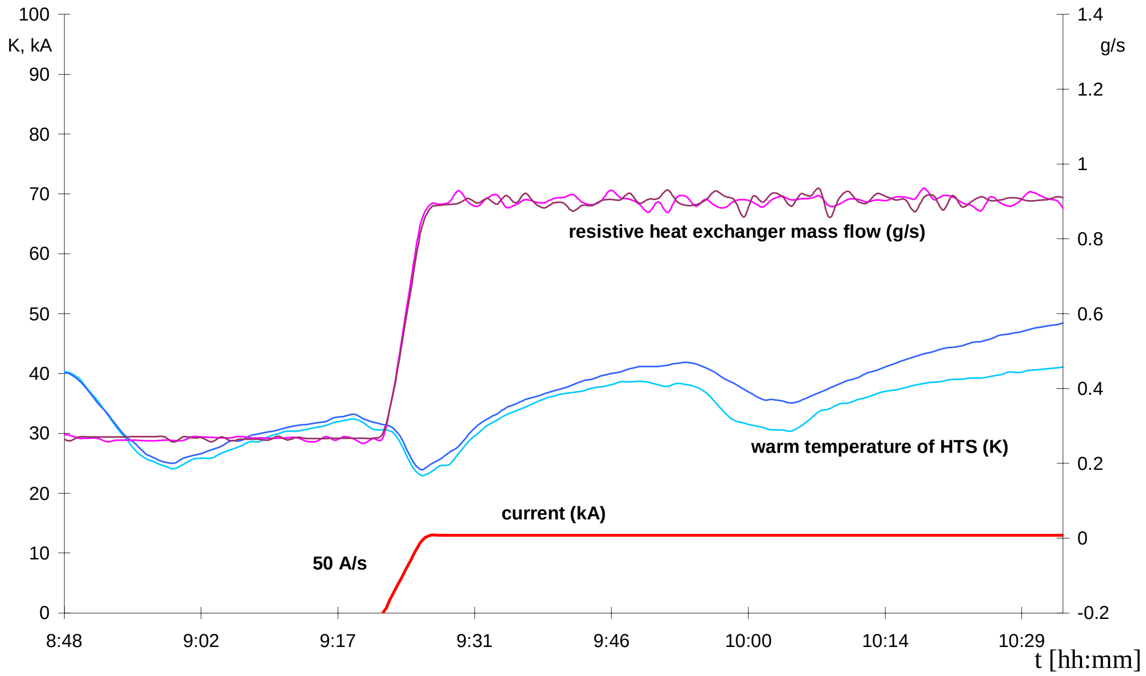

Figure 6. Typical current ramping of leads with control of the mass flow through the resistive heat part.

Table 2. Typical test results of a HTS lead pair

lead A lead B	HTS warm end [K]	20 K mass flow [g/s] 0 kA	Pressure drop [mbar] 0 kA	H.L. 4.5 K bath [W/lead] 0 kA	20 K mass flow [g/s] 13 kA	Pressure drop [mbar] 13 kA	H.L. 4.5 K bath [W/lead] 13 kA
CERN Specification	**< 50**	**< 0.6**	**< 50**	**< 1**	**< 1**	**< 50**	**< 1.5**
Measurement of a typical lead pair	**40** **40**	**0.42** **0.45**	**2.6** **1.9**	**0.73** **0.73**	**0.82** **0.86**	**3.3** **4**	**0.85** **0.85**
Precision	**+/- 0.1**	**+/- 0.01**	**+/- 1**	**+/- 0.05**	**+/- 0.01**	**+/- 1**	**+/- 0.05**
Stability	**+/- 0.5**	**+/- 0.03**	**+/- 1.5**	**+/- 0.08**	**+/- 0.1**	**+/- 3**	**+/- 0.08**

After having completely characterized the current leads in terms of their thermal performances (20 K mass flow at 0 and 13 kA, pressure drop over the heat exchanger, stability of the heat exchanger at various HTS temperatures and heat loads on the 4.5 K liquid helium bath), the control system can be set-up to control a constant mass-flow of 20 K GHe in the heat exchanger for each current value (Figure 6). This mass flow varies linearly with the current passing through the leads between its value measured at 0 A and 13 kA. The advantage of this control method is the stability and fast response achieved, independent from the temperature of the warm end of the HTS. Therefore the HTS remains below its maximum operating temperature value, otherwise an interlock prevents or aborts powering of the leads. The disadvantages are that the leads needs to be tested to set the control parameters (mass flow at 0 and 13 kA) and additional instrumentation is needed (flowmeter).

CONCLUSIONS

A low heat inleak test cryostat has been successfully designed, commissioned and operated at CERN to test prototype 13 kA HTS current leads.

Several pairs of HTS current leads have been tested and have shown that the cryogenic requirements set in the technical specification can be met. These leads have demonstrated that the heat load into the liquid helium bath can be reduce by a factor of up to 19 with respect to conventional self-cooled leads, however at the cost of GHe cooling at 20 K.

Additional tests to demonstrate the long term reliability (thermal and electrical cycles) will be performed.

Another test cryostat for 600 A HTS current leads of a similar design has been built and will be commissioned shortly for the test of prototype 600 A HTS leads.

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